Benefits of Including Battery Electric Cars in Electric Road Systems: Battery and infrastructure savings

Abstract—**The newly emerged electric road system (ERS) technology, mainly considered to electrify long-haul trucks, has the advantage of charging passenger battery electric vehicles (BEVs). Using detailed GPS-logged movement patterns for 412 private conventional cars in Sweden, this study models the potential benefits for passenger BEVs using ERS. The study shows that ERS aiming to electrify long-haul trucks can cover most private vehicle trips with home-only stationary charging and small battery ranges (68-101 km), or alternatively eliminate all stationary charging needs for private vehicles with large battery ranges (136-606 km). The study points out that ERS utilization is independent of the total travel distances of car users and depends more on visited locations and residency. The economic benefits from reduced battery capacities with ERS can be large compared to the ERS infrastructure costs, even when BEVs constitute a relatively low share of the vehicle fleet. When planning ERS infrastructure for trucks and buses, the economic benefits from passenger BEVs can be large and therefore can also be considered.**

Index Terms— **Electric road system, Dynamic charging, Electric battery, Battery electric vehicle, Electric charging infrastructure.**

I. INTRODUCTION

In Sweden, transport accounts for roughly 30% of CO2 emissions [1], and passenger cars represent about 60% of these emissions [2]. Electrification of transport, such as switching to electric vehicles, can mitigate these emissions, especially in Sweden, which has relatively low emissions from electricity production. The newly emerged technology electric road system (ERS) for electrifying long-haul trucks transfers electricity to vehicles dynamically while driving on-road. Different ERS technologies have been developed and tested at small scales, ranging from a few hundred meters of test sites to kilometers of public roads in Sweden, Germany, and the U.S. [3], [4].

ERS connecting Sweden and Germany is already being considered at the high level. Governmental agreements between the two countries are initiated with the aim of intensifying cooperation in ERS research [5]. Germany is considering overhead ERS technology that serves only heavy vehicles [6] while Sweden is still testing different technologies for different vehicle types. Other neighboring countries, e.g., Norway and Denmark, newly start considering ERS for fleet electrification as well [4], [5], [7], [8].

However, heavy vehicles constitute only 4% of all vehicles in Sweden and contribute to 18% of the total emissions from vehicles whereas passenger cars are about 94% of all vehicles and contribute to 67% of total emissions from vehicles [9], [10]. Charging passenger battery electric vehicles (BEV) on the road would increase the utilization of ERS infrastructure and therefore improve its value. The battery is an expensive component of a BEV, e.g., the battery constitutes 30% of the price of a Chevrolet Bolt with a 400 km battery range [11]. A reduction in the battery capacity required to meet all driving needs would significantly decrease BEV prices [12], possibly encouraging more people to buy them [13]. The reduction to battery capacities also would solve many large scale adaptation challenges hindering car user from switching to the BEV, e.g., limited travel range and long charging time [12], [14], [15]. Given that there are large technology lock-in effects and path dependencies in the development towards a large-scale ERS system [16], a thorough assessment is needed to make a deliberate and informed choice.

A. Literature review

Recent research has inspected the economic and environmental impact and infrastructure rollout of implementing a large scale ERS in different places around the world and propose placing them on roads with highest traffic [7], [9], [12], [16]–[19]. Reference [7] investigates the economics for BEV with and without electric roads in Denmark. The study compares the results to those for conventional vehicles, concluding that BEV on ERS is the most viable option. Reference [20] inspects the potential for dynamic charging to address range and recharge issues of BEV in California, USA. Reference [21] predicts 80% reduction in BEV battery capacity with inductive ERS compared to stationary charging only. References [22] and [9] show that installing ERS in Sweden that serves both heavy and passenger vehicles results in huge added value to society and reduces costs compared to conventional stationary charging. Reference [3] suggests that using ERS to charge vehicles attracts more drivers and generates more revenue than stationary charging. Reference [8] investigates the electrification of E39 in Norway and the charging pattern and its impact on the electricity system. Reference [17] analyzes the societal cost benefits of implementing ERS to Denmark that can be used both by commercial and passenger vehicles. Finally, Reference [12] shows the huge economic and environmental impacts of implementing an ERS that serves all vehicle types in the USA.

The effects of an ERS on BEV charging and battery capacities/ranges from these studies were based on general assumptions of vehicle use and driving patterns. For example, [20] assumes travel pathways that approximate the route an BEV might take between pairs of origins and destinations. References [22] and [9] attempt to minimize the system costs by assuming arbitrary percentage shares of electric driving over the total travel distance. Reference [8] also assumes a share of travel distance for vehicles in Norway while using E39. Reference [23] uses a macroscopic model with mathematically tractable means to characterize the deployment and operation of ERS and stationary charging. None considers the real movement patterns of cars and integrate that with probable locations of ERS. An exception is the study of [12] in which detailed driving patterns in six U.S. cities surveyed between 2001-2015 are used to explore ERS benefits. However, the study assumes two arbitrary battery ranges and BEVs can be charged whenever and wherever stopped for more than one hour.

B. Our contributions

Lacking individual car movements details hinders previous studies from accurately estimating battery ranges for the BEV fleet and potential economic effects associated with large scale ERS deployment. Without realistic understanding of charging power demands and revenues given charging options, it also hinders policymakers from making informed decisions. To the best of our knowledge, there has not been any research published on the effects and implications of reduced battery ranges for BEVs charging on ERS based on individual vehicles' real driving patterns. Such data capture useful information at the level of individual cars, e.g., travel distance, range limitations, utilized roads, parking areas/time, and home location for each car.

This study proposes a methodology that provides detailed and more realistic insights into required battery range, charging patterns with/without ERS, and evaluate their economic impacts more accurately. Based on real-life individual movement patterns for passenger cars in Sweden and a detailed geographic information system (GIS)-based infrastructure system, the study assesses the impact and benefits to passenger BEVs of ERS by 1) identifying the ERS utilization in different ERS placement scenarios, 2) identifying the potential reduction in battery ranges while fulfilling all driving requirements, 3) estimating the economic benefits from potential reduction in battery ranges and stationary charging infrastructure, and 4) investigating the ranges of shares of electric driving met with ERS vs. stationary charging.

II. METHODOLOGY

This study proposes several ERS placement scenarios in Sweden, see section II.A. The study simulates the battery state of charge (SoC) of BEVs according to the detailed movement patterns of 412 privately driven cars in Sweden. The car movement patterns and ERS coverage are mapped to the Swedish road network using GIS, see section II.B. The impact of the ERS on charging events on the roads, required battery range, and economic benefits will be examined given different assumptions of the ERS placement, charging-rate, and the availability of stationary charging, see sections II.C- II.F.

A. Electric Road System

This study investigates large-scale implementation of ERS using road-traffic data (i.e., the average daily traffic) provided by the Swedish Transport Administration [24]. The European (E) and National (N) roads constitute 4% of Sweden's total road length [24] while encompassing more than 50% of the national vehicle traffic counts (that is, all traffic, including cars, trucks, and busses, etc.) [4].

This research applies ERS to different cases of the Swedish E and N roads that include different lengths and traffic volumes: E roads only, N roads only and the 25% of both E&N road, E&N25 (and include 50%, 75% and 100% in the sensitivity analysis, or E&N50, E&N75 and E&N100, respectively) with the most traffic prioritized by truck traffic volume (Fig. 1). Truck traffic is used to prioritize road selection as it is assumed that ERS is mainly implemented to electrify heavy vehicles while passenger cars also benefit from that. While most (88%) of the traffic on the selected roads are passenger cars, the difference between selecting roads by truck traffic or by all vehicles is still not very large; the overlap is 90% for the two methods. E roads and N roads are almost equal in total length, whereas the E roads cover about 58% of the truck traffic on these roads. E&N25 and E&N50 cover about 53% and 81%, respectively, of the truck traffic on both E and N roads.

For simplicity, the ERS charging rate is assumed proportional to the energy use rate of each vehicle. Also, each BEV is assumed using energy dependent only the distance driven, i.e. having a constant specific energy use *e* (kWh/km) independent of, for instance, speed, road conditions, traffic, load, and weather. In the main scenario, the research examines ERS with a charging rate for cars of 2*e* (which thus corresponds to an added range of 2 km per km of ERS). ERS charging rates of e and 4e are also inspected to provide insight into the impacts of charging rate. Charging rate *e* maintains the vehicle's battery state of charge (SoC), whereas higher charging rates recharge the batteries and increase the SoC while driving on ERS.

The assumptions mean that charging power increases linearly with vehicle speed, and, for example, when driving at 100 km/h and using 0.18 kWh/km, the ERS charging power is 18, 36, and 72 kW, for the rates e, 2e, and 4e, respectively. 72 kW per car will add up to around 1 MW/km ERS lane at full traffic. For comparison, other studies have considered ERS for BEVs with different charging power between 20-60 kW with different efficiencies [12], [15], [21], [25], [26].

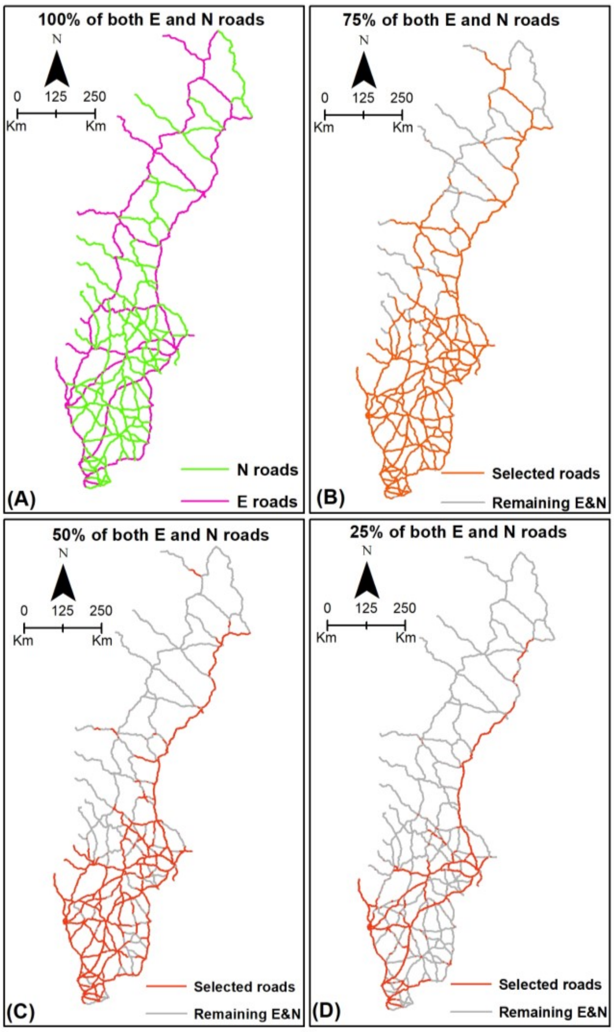

Fig. 1. European (E) and National (N) roads in Sweden and the road segments with the top *100% (A), 75% (B), 50% (C), and 25% (D) truck traffic volume*

B. Car movements patterns

The study uses GPS measurements data from the Swedish Car Movement Data project [27] to describe the movement patterns of individual cars. Private and company cars were selected by a stratified sampling by ownership (company car/private car), car age (0-3/3-8yrs), car weight (≤1500/>1500 kg), fuel type (diesel/non-diesel), residency (city/non-city)) in western Sweden. Each car was measured for about two months. The GPS loggings were performed during 2010-2012 and cover all seasons. The dataset is considered representative for all of Sweden in terms of urban and rural areas, city size, household size, income and population density, car size, and car fuel type [28] and has among other things been used to study implications for the electricity system of road electrification in Sweden [4], [8].

Only cars that have at least 30 days of GPS measurements are selected for further analysis, resulting 412 cars with loggings for 30-80 days. Trips or trip parts occurring outside Sweden are excluded in this study.

The residences of the drivers are classified as urban or rural based on overlaying their home parking locations with the land-cover/land-use data obtained from the European Union's Earth Observation Programme [29], as implemented in [30], [31]. A third of the drivers resides in rural areas whereas the remaining drivers reside in urban areas. On average, the rural cars are driven 17% annually more than the urban ones. It can be noted that the average extrapolated annual travel distance for these Swedish cars (22 155 km/year) is higher than the average for all American cars (≈18 000 km/year) [12], probably due to these cars are sampled from the newer half of the fleet (< about 8 years).

C. Stationary charging

This study considers three stationary charging scenarios: “home-only stationary charging” (HomeSC), “home and other stationary charging” (MixedSC) and “no stationary charging” (NoSC). HomeSC is considered as the main charging strategy to complement with ERS. The two other stationary charging patterns are investigated to illustrate the dependency on other charging while using ERS. In MixedSC, drivers complement their home charging with other non-home stationary charging. In NoSC, drivers use only ERS to charge their BEVs. This represents an extreme case and is set up to investigate the possibility of complete independence of stationary charging.

The study applies a temporal approach to identify charging occasions for the two charging strategies, i.e., HomeSC and MixedSC. For our main charging scenario (i.e., HomeSC), stationary charging events occurs when parking time exceeds 10 hours, or 8 hours if the parking time includes 03:00 am. This is meant to effectively pick out home/overnight parking [32], at which the study assumes cars have access to chargers. In the MixedSC case, stationary charging event occurs when the parking time exceeds 4 hours, which the research identifies as home and other charging points such as public or work. The resulting mean (95th percentile) trip distances for HomeSC and MixedSC scenarios are 57 (190) and 40 (132) km, respectively.

D. BEV energy use and required battery range

The minimum required battery range to fulfill each trip starting from a full battery is calculated with and without ERS. In all three stationary charging scenarios, cars are assumed to start their respective trips fully charged (i.e., SoC is 100%). When driving on an ERS road, they simultaneously add energy to their batteries at rates depending on the various assumed ERS charging rates, or, when the battery is full, at rate to maintain 100% SoC. The required battery range for each car is then taken as the maximum of the estimated minimal required battery range for any of the car's trips.

E. Battery savings

The estimated lithium-ion battery price is assumed to be ~106 €/kWh between 2025-2030. The price has continuously dropped with technological advances and scale of production, from ~250 €/kWh in 2015 [13], [33], [34] to 160-207 €/kWh in 2017-2019 [35]–[37]. The battery price is expected to drop further to reach a range of ~85-135 €/kWh in 2025 [33], [36]. In a similar analysis to estimate the economic benefits of small batteries, [12] considers battery cost of ~190 €/kWh. To achieve cost competitiveness with combustion engine vehicles, [33], [36] argue that the battery cost needs to fall below ~106-126 €/kWh. Therefore, our estimated cost savings from reduced battery capacity (range) with 106 €/kWh could be considered conservative. The monetary savings from the reduced average battery range with ERS are shown in the following equation:

$$S_B = (R_{baseline} - R_{ERS}) \times e \times P_{unit\,B} \times V \times \sigma \times \beta \tag{1}$$

where S_B is total savings from reduced battery range for the given BEV fleet share, $R_{baseline}$ and R_{ERS} are the average needed battery ranges without and with ERS, respectively. The average specific energy use *e* is assumed to 0.18 kWh/km, equal to the average specific energy use of a VW e-Golf [38]. $P_{unit\,B}$ is the expected market price of a battery (€/kWh), V is the number private passenger vehicles in Sweden, σ is the BEV share of the vehicle fleet, and β is the number of generations of batteries saved during the ERS lifetime = ERS lifetime / BEV battery lifetime. For ERS, a technical lifetime of 35 years is expected, which is similar to what is typically applied for railway investments [39]. Assuming that an electric battery would serve up to 15 years [7], [12], this yields at least two batteries within the ERS lifetime. Therefore, the study assumes the economic benefits of two reduced battery capacities for each

BEV examined, i.e., β is set to 2.

F. ERS costs

Several studies and reports have estimated the ERS infrastructure cost with large uncertainty at present mainly due to: 1) that ERS is still an immature technology under development, and 2) the limited experiences from the different ERS test sites at small scales on public roads [4]. The Swedish Transport Administration provides estimates for several technologies that are currently being tested in Sweden with a range of 1.2-2.0 M€/km [40]. However, the German Institute for Energy and Environmental Research estimates the infrastructure cost for catenary ERS in the range of 1.7-3.1 M€/km [6]. Other studies and reports estimate the inductive and conductive ERS technologies the range of 0.4-2.7 M€/km, including the components for both the electric road infrastructure in both directions and the electricity distribution to the road [4], [12], [16], [40], [41]. The research considers two ERS cost estimates: a low estimate of 0.4 M€/km and a high estimate of 2.7 M€/km. The study also assumes, as in [12], that maintenance costs associated with ERS are equivalent to the maintenance costs of conventional roadways. Utilizing this system in both directions of two-way roads yields 4,690 km and 18,770 km of ERS for E&N25 and E&N100, respectively.

G. Stationary charging infrastructure costs

The EU considers two types of stationary charging infrastructure for EVs according to their power rate: slow charging points with power rating below 22 kW and fast charging points with power rating above 22 kW, which charge a battery capacity of 18 kWh in 4-8 hours and 20-30 mins, respectively [42]. On the other hand, the cost for each charger differs: on average about €2,000 and €75,000 per slow (i.e. power rate of 6.6 kW) and fast charger (i.e. power rate of 50 kW), respectively, including equipment and installation [42]–[44]. The expected lifetime of a charger is about 10 years on average [44], which means that within the lifetime of an ERS at least 3 chargers of each type would be required at corresponding charging locations. In this research, home charging could be implemented with a 6.6 kW power rating charger but only with small battery capacities or if drivers do not drive very long distances every trip. The infrastructure cost for home charging ($C_{home\ infra}$) is calculated using the following formula:

$$C_{home\ infra} = \sigma \times V \times N_{charger} \times C_{slow\ charger} \tag{2}$$

where σ is the BEV share, V is the total number of vehicles in Sweden, $N_{charger}$ is the number of installed chargers in ERS's life time, i.e., $N_{charger}$ is set to 3, and $C_{slow\ charger}$ is the 6.6 kW power rating charger cost. Here, 6.6 kW chargers are installed at home, with complementary chargers at other public/work locations for MixedSC. Current EU regulation requires member states to set up policy frameworks that will provide at least one publicly accessible charging point per every 10 BEVs [45], of that 15.3% are estimated to be fast (i.e., power rating of 50 kW) chargers in Sweden [46]. The charging infrastructure cost at other public/work locations ($C_{non-home\ infra}$) is calculated using the following formula:

$$C_{non-home\ infra} = \frac{\sigma}{10} \times \mathrm{V} \times N_{charger}\left(0.153 \times C_{fast\ charger} + 0.847 \times C_{slow\ charger}\right) \tag{3}$$

where $C_{fast\ charger}$ is the 50 kW charger cost

III. RESULTS

A. ERS utilization

For each BEV, the study derives the ERS share of driving as the percentage of driving distance on road equipped with ERS to total travel distance for each ERS placement case, see Fig. 2.

Obviously, applying ERS to more road lengths increases the ERS share of driving, but with diminishing returns. Increasing the ERS distances from E&N25 to E&N50, E&N75, and E&N100 increases the average charging distance share successively by 6, 3, and 1 percentage points, respectively, to reach a maximum of 49%.

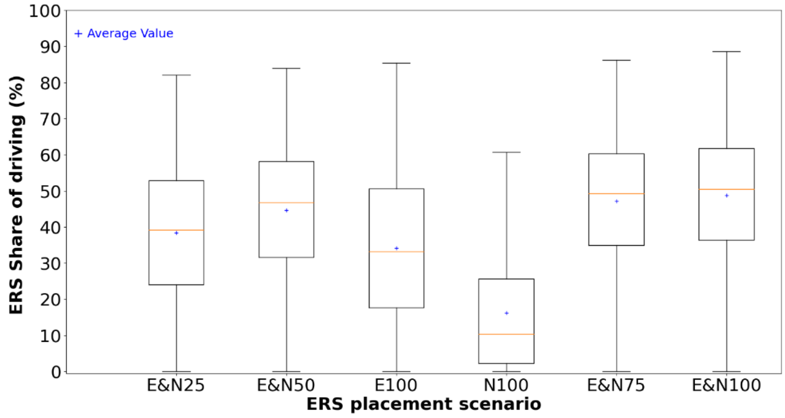

Fig. 2. Box plots for the ERS share of driving in six ERS scenarios. E&N25, E&N50, E&N75, and E&N100 refer to scenarios with ERS placed on 25%, 50%, 75%, and 100% of both E and N roads, respectively, measured by traffic volume. E100 and N100 refer to European (E) and National (N) roads only, respectively. The scenarios are ordered according to road length from the shortest on the left to the longest to the right, although E&N50, E100 and N100 have roughly the same road length.

The placement of ERS is also important. Even though the total lengths are equal for E and N roads, with almost 50% each, their contributions to the charging distance are very different, with N roads performing notably worse. Also, E&N50 results in higher charging distance shares (mean 45%) compared to 100% of E roads alone or 100% of N roads alone.

In the following analysis, the study shows E&N25 as the main scenario for ERS placement and compares it with E&N100 in the sensitivity analysis.

It is noticed that urban residents could have higher ERS share of driving compared to rural residents. Also, the ERS share of driving is not highly dependent on the total driving distance for each car. But, cars with long annual driving (> 40,000 km/ year) have higher ERS share of driving compared to cars with very short annual driving. That is shown in Fig. 3, where the ERS share of driving and total travel distance for each car are illustrated. Urban residents have ERS share of driving (54%), on average, compared to rural residents (48%) in both ERS placements. The linear regressions for both E&N25 and E&N100 have very low coefficients of determination (R^2) of 0.10 and 0.16, respectively, suggesting a weak relationship between ERS share of driving and total travel distance. Noticeably though, some BEVs utilize ERS minimally. Even for E&N100, about 7% of the cars drive on ERS roads less than 20% of their total travel distances. However, the cars with low (< 20%) ERS share of driving tend to have short annual travel distances. On the other hand, cars with long annual driving (> 40,000 km/ year) have high average ERS share of driving of about 66%.

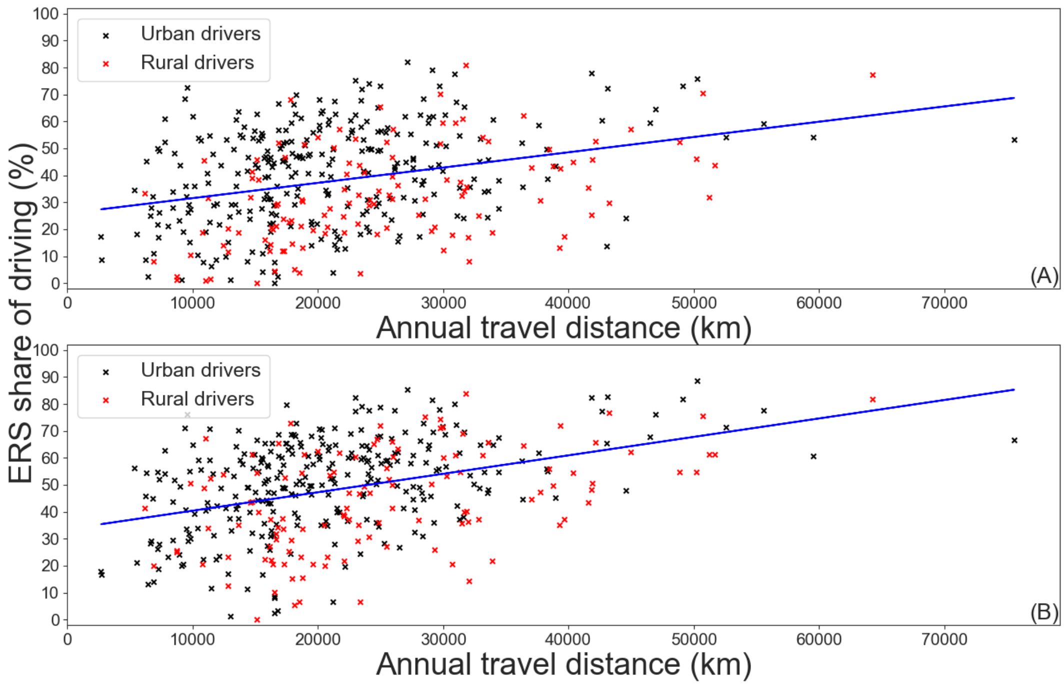

Fig. 3. Share of charging distance for individual cars versus annual travel distance for A) E&N25 and B) E&N100 as ERS for urban and rural cars. Blue lines are linear regressions for the annual travel distance and ERS share of driving for both drivers.

B. Reduction in battery size

The study shows the possible reductions in battery ranges with different ERS charging rates and placements by estimating the required minimum battery range for each individual car. The battery range required to cover all driving, sorted from small to large, and the median battery range for each case are shown in Fig. 4. In the absence of ERS, in the HomeSC scenario, the median range to complete all driving is 266 km (Fig. 4.A) and 95% of the cars require ≤ 655 km battery, which is still bigger than existing batteries available on the market[1]. This suggests that HomeSC is not a realistic charging scenario giving available market battery range.

Utilizing E&N25 (2e) with HomeSC yields a median reduction in battery range of 62%, to only 101 km (Fig. 4.A). E&N100 further decreases battery ranges, with a mean total reduction of 71%, to 78 km (Fig. 4.B). A reduction of the charging rate on E&N25 from 2e to e yields an increase of average battery range by 26%, whereas a doubling to 4e decreases the average battery range by only 12% (Fig. 4.A).

[1] For reference, the battery range for Tesla model S is about 416-555 km.

For MixedSC, results are very similar to the HomeSC case.

Comparing the required battery ranges when eliminating all stationary charging (NoSC) with the no-ERS scenario or an ERS with a charging rate of only e kWh/km is meaningless; therefore, the study only shows the battery requirements for ERS (2e) and ERS (4e) cases. NoSC requires median battery ranges of 606 km for E&N25 (2e) (Fig. 4.E). Increasing the ERS lengths to E&N100 reduces the median battery ranges to 288 km (Fig. 4.F). Doubling the ERS charging rate to 4e decreases the required mean battery ranges considerably, by 42-52% (Fig. 4.E and F). This implies that relying completely on ERS without any stationary charging stations would be facilitated by higher charging rates to keep battery ranges down, but still on larger battery ranges would be required.

The required battery ranges for urban and rural residents differs depending on the charging pattern, see, for example, Table 1 for ERS (2e). For the E&N25 system with stationary charging, rural residents require 15-18% larger median battery ranges than urban residents. With the ERS extended to E&N100, this difference between rural and urban residents increases. The larger rural batteries required are partly due to the additional annual driving.

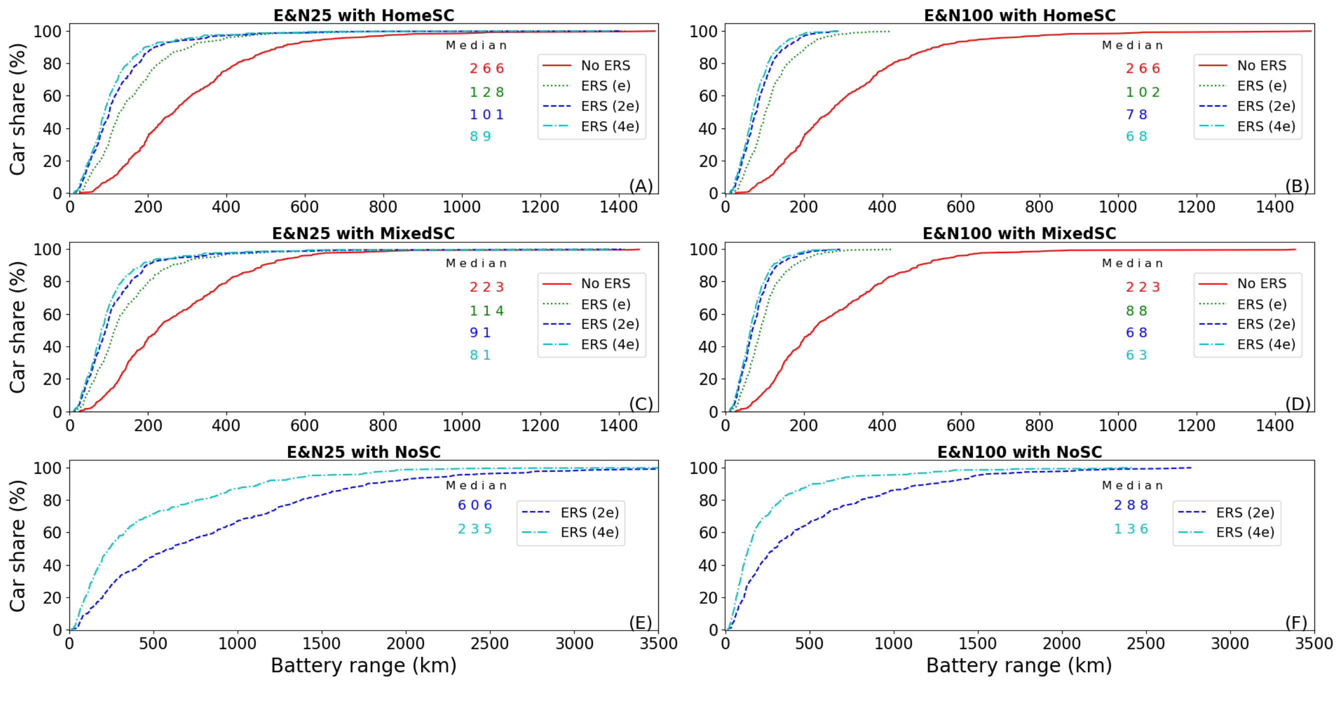

Fig. 4. Cumulative share of cars for required battery ranges to cover all driving in the 25% of E and N roads (E&N25) case (left) and 100% of E and N roads (E&N100) case (right). The numbers in the boxes are the median battery ranges required to meet all driving. Note that x-axis range for A-D is different than for E and F. HomeSC: Home-only stationary charging, MixedSC: Home and other stationary charging, NoSC: No stationary charging.

Without stationary charging, rural residents need further larger battery ranges: the rural residents require 127% (E&N25) and 96% (E&N100) larger batteries. On the other hand, urban residents have higher ERS share of driving and thus utilize ERS more regularly, which reduces battery range requirements without stationary charging.

TABLE 1
THE MEDIAN OF BATTERY RANGES FOR RURAL AND URBAN DRIVERS WITHOUT/WITH ERS (2*e*).

Charging pattern	*ERS placement*	*Median battery range (km)*		
		All residents	Rural residents	Urban residents
HomeSC	No ERS	266	278	262
	E&N25	101	110	93
	E&N100	78	90	70
MixedSC	No ERS	223	227	220
	E&N25	91	98	85
	E&N100	68	76	65
NoSC	E&N25	606	1021	450
	E&N100	288	486	248

C. Shares of electric charging on ERS

The study evaluates the minimum required battery range for each car to fulfill all its driving. Minimum battery ranges with ERS and stationary charging assume BEV drivers use both options without any preference or barrier. However, it is still unclear whether conditions on ERS are going to motivate users to utilize this charging option more than stationary charging or if it is the other way around [12]. The potential battery reduction with ERS presented earlier assumes that car drivers maximize their recharging whenever infrastructure is available along their driving and at stops. But, for a given minimum battery ranges, car users could still maximize or minimize their ERS charging shares based on their own preference such as economic considerations.

A big difference in ERS charging shares is noted when cars maximize or minimize their ERS utilization. Average shares of ERS charging for BEVs using their minimum vehicle battery ranges, shown earlier in Fig. 4, for both extreme cases are illustrated in solid thick lines in Fig. 5. The two extremes gradually decrease with increased minimum battery ranges due to more reliance on stationary charging for long trips outside ERS roads.

Car users might utilize bigger battery ranges than the minimum required to avoid range anxiety. The effects of increased battery ranges in step of 28 km (~5 kWh at 0.18 kWh/km) are also given in Fig. 5. Maximum ERS charging is insensitive to increased battery ranges. However, increased battery ranges significantly influence minimized ERS charging shares, especially starting from small minimum battery ranges. Assuming that the minimum BEV battery range for the fleet is 111 km (~20 kWh), the average minimum ERS charging shares are still around 20% and below. Further increasing the minimum BEV battery range to 222 km (~40 kWh) reduces the shares to below 10%.

D. Total cost savings with ERS

The economic benefit of reduced battery ranges also depends on the number of passenger cars switching to BEVs. The total number of passenger cars in Sweden is about 4,871,000 [47]. The study assumes that the sampled cars represent all Sweden's passenger vehicles; thus, all private vehicles in Sweden follow the distributions of reduced battery ranges found in Fig. 4. Also, the ranges are converted to battery capacities (kWh) using the aforementioned energy use assumptions. The study presents savings in two assumed orders of BEV penetration: 1) drivers with the highest battery capacity savings switch to BEV first (optimal), and 2) drivers switch in random order to BEV (random). The two orders ease exploring the boundaries of economic benefits at early stages, the maximum with optimal order and average estimates with random. The research calculates the saved battery capacities costs for all BEVs with each charging pattern using Equation (1).

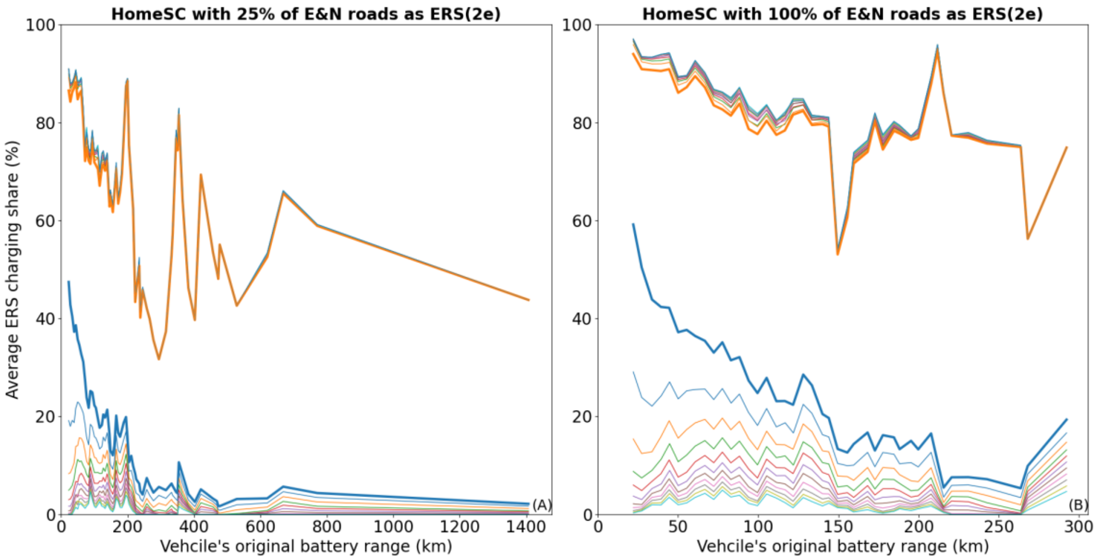

Fig. 5. Maximum (in solid thick orange) and minimum (blue) average ERS charging shares by minimum vehicle battery ranges given (A) E&N25 and (B) E&N100 and for home stationary charging (HomeSC) scenarios. The effects of increased battery ranges beyond the minimum battery requirement are shown in different thin colored curves in step of 28 km (5 kWh at 0.18 kWh/km).

The savings resulting from smaller battery capacities as a function of BEV penetration with ERS are shown in Fig. 6. The two horizontal lines show the range of ERS cost estimates (low in green and high in yellow). With HomeSC, implementing E&N25 results in large net benefits within the range of both ERS costs (Fig. 6.A). Even with high ERS cost estimates, the cost is covered if 15% and 34% of cars switch to BEVs, in the optimal and random scenarios, respectively. For MixedSC, given the smaller savings from reduced battery capacities, BEVs have to make up 18% and 40% of the fleet in the optimal and random scenarios, respectively. For E&N100, only a low ERS cost would yield positive net savings (Fig. 6.B). In both HomeSC and MixedSC, increasing the charging rate does not increase the net savings significantly. However, the HomeSC has more absolute reduction in battery size (Fig. 4) and thus higher net savings.

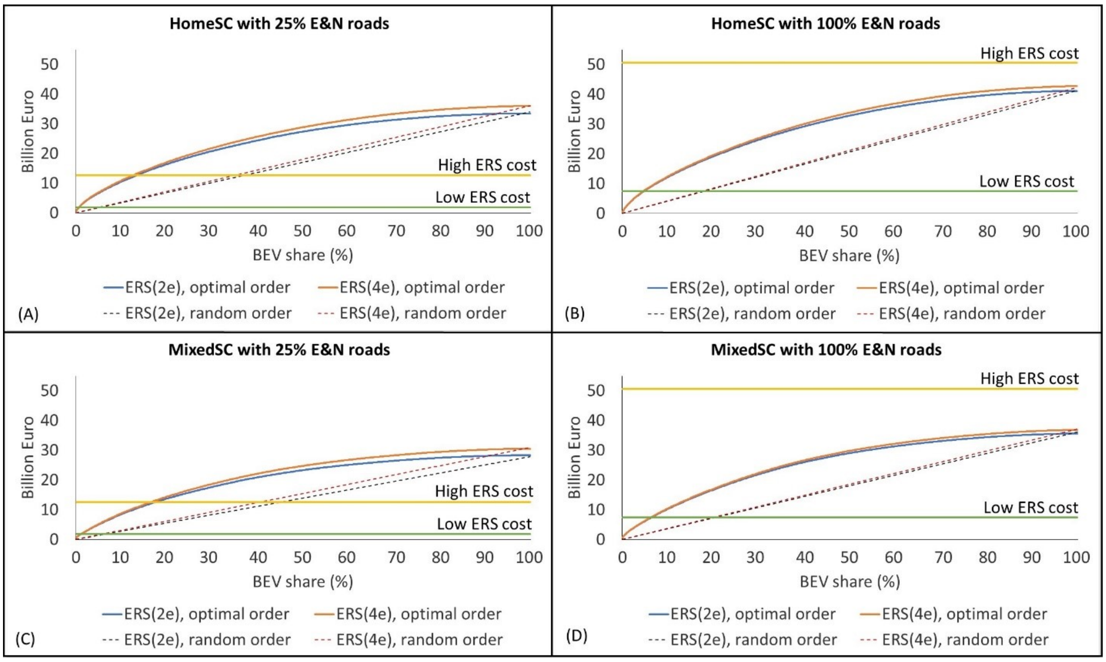

Fig. 6. Savings in billion euros from reduced battery capacity required as a function of BEV penetration level with A) HomeSC and E&N25, B) HomeSC and E&N100, C) MixedSC and E&N25 and D) MixedSC and E&N100 with 2e and 4e charging rates. The savings are calculated based on Equation 1. HomeSC and MixedSC refer to Home-only stationary charging and Home and other stationary charging, respectively.

Overall, ERS would provide relatively high net savings in some considered cases compared to its cost. Here, net savings consider the total savings or extra costs from constructing stationary chargers and ERS infrastructure as well as reduction in the required battery capacities. High ERS cost estimates built for passenger car use are considered to illustrate conservative net savings. Without ERS, HomeSC requires high initial investments in both large BEV battery sizes and infrastructure in the form of home chargers. The cost of charging infrastructure for HomeSC is estimated to be €32 billion for a passenger fleet that is 100% BEV. Compared to that base case, i.e., HomeSC with no ERS, max net savings of including ERS (4e) in each considered charging pattern are illustrated for a 100%-BEV fleet in Fig. 7.

With ERS, both HomeSC and MixedSC scenarios require smaller initial investments given the reduction in the battery sizes. HomeSC with E&N25 could provide net savings of €23 billion, which is the highest among considered cases. Extending ERS to E&N100, the higher ERS cost would eliminate the savings from reduced battery sizes, yielding negative net savings. MixedSC saves even more from reduced battery sizes but also requires additional stationary charging investments of €20 billion to cover a 100%-BEV fleet. Net savings with MixedSC are thus less than for HomeSC in both placement scenarios. NoSC requires BEVs with larger batteries, especially for E&N25. Thus, relatively high investments in vehicles are expected at early stages. Reduction in infrastructure costs and battery sizes are not enough to cover high ERS costs in any ERS placement scenario.

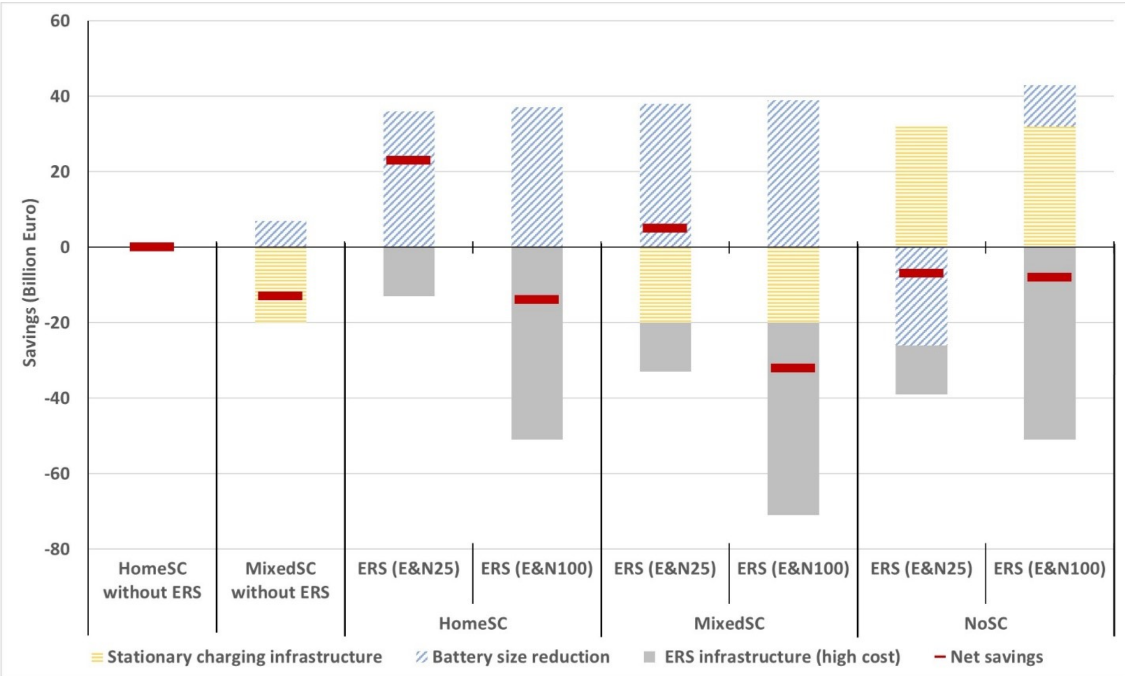

Fig. 7. Savings and extra charging infrastructure costs of Home-only stationary charging (HomeSC), Home and other stationary charging (MixedSC) and No stationary charging (NoSC) with ERS and MixedSC without ERS for 100%-BEV share compared to HomeSC without ERS.

IV. Discussion and Conclusions

This study adds insights by using the detailed driving patterns of conventional vehicles to investigate the possible benefits of implementing an ERS in Sweden that can also be used by private passenger BEVs. In summary the study shows that ERS aiming to electrify long-haul trucks can cover most private vehicle trips with home-only stationary charging and small battery ranges (median 68-101 km), or alternatively eliminate all stationary charging needs for private vehicles with large battery ranges (median 136-606 km). The study finds that ERS utilization and battery ranges are independent of the annual travel distances of car users and depends more on visited locations and residency. The economic benefits from reduced battery capacities with ERS are large compared to the ERS infrastructure costs, even when BEVs constitute a relatively low share of the passenger vehicle fleet. This depends on many factors such as placement and the specific costs of ERS. To maximize benefits, shorter ERS placement lengths with the highest traffic should be considered. The study illustrates that BEVs with small batteries require both ERS and stationary charging, both complementary to each other. When planning ERS infrastructure for trucks and buses, the economic benefits from passenger BEVs can be large and therefore can also be considered.

In the continuation, some issues and implications of the study are discussed in more details.

1) Data and analysis

The data and the analysis have limitations and assumptions that can influence the results. The analysis is limited to Sweden, both regarding the ERS and the driving patterns but the methodology could be implemented elsewhere in case similar data are obtained.

In the estimate of saved battery range with ERS, the difference in minimum required battery range between without and with ERS is considered, see Fig. 4. This led to an average battery range saving of 180 km (or 32 kWh) per car in the main case scenario of E&N25(2e) with HomeSC. The considered analysis yields very small to large batteries ranges. BEVs with very small battery ranges are not certain to be materialized though. Considering current BEV market ranges (i.e., 150-500 km) with ERS, the savings in battery ranges would decrease to an average of 140 km, which is about 20% less than considered earlier. This is still relatively high reduction in battery ranges. However, 15% of the BEVs do not have to change their battery range at all because they already have the smallest battery without relying on ERS.

Including cars from other regions of the country would have strengthened the findings. But does the home location of the surveyed cars in Western Sweden provides a representative battery range saving potential for all Sweden? Considering the placement of E&N25, see Fig. 1.D, it is obvious that other regions, but not Western Sweden, are not covered by the ERS. The estimated potential is probably reasonable for those parts of Sweden with a relatively high population density, but apparently an overestimate for others.

Moreover, the change in travel behaviors are assumed to be negligible over time and when switching to BEV. Similarly, [12] assumes travel patterns for cars in 2001 are representative for the USA case. However, by adapting the use of their cars, multicar households have the option to use a short-range BEV together with a longer-range car, which also could be a BEV [48]. Thus, such a large battery as calculated in some cases may not be needed for some of the cars.

Additionally, the dataset includes newer cars at the survey time, and newer cars tend to drive longer annual distances [49]. Thus, the analysis probably accounts for cars with required battery capacities/ranges that are above average, and for a larger share of the older cars a smaller battery may be enough even without ERS. On the other hand, these older cars have once been newer and therefore maybe been driven more and fitted with a larger battery if there was no ERS. Furthermore, the dataset includes patterns for privately driven vehicles only, not all current vehicles in Sweden, such as taxis, company cars, etc. Also, the study assumes no growth in car numbers up to 2025-2030.

The analyzed stationary charging patterns assume drivers can fully charge their cars at each identified parking, which might not be the case. Fully charging the battery depends on the availability and types of charging points. The study assumes that charging points are available wherever and whenever needed but with much restricted conditions and more realistic charging scenarios compared with [12]. Missing charging points would result in increasing a trip's travel distance, possibly increasing the battery range required for stationary charging. Lastly, the analysis could be expanded to include more vehicle types to further illustrate a wider range of probable ERS utilization and benefits. Thus, the introduced benefits could be considered a minimum and limited to private vehicles only.

The literature is still uncertain regarding the costs of infrastructure for electrification especially for ERS but also for any feasible stationary charging system outside the home. Also, given that the charging power will be higher for trucks than for cars, the study assumes that including the latter will not affect decisions about dimensions nor ERS costs. Moreover, many companies have tested different ERS inductive and conductive technologies with different power rates and different cost estimates. Thus, the study excludes any ERS cost dependency on the charging rates for cars. The study also does not consider any dependency of road traffic on investment costs of electricity supply, which might not be the case. The infrastructure cost figures are therefore by necessity and deliberately crude, but, at this stage of development, the authors think this type of order-of-magnitude estimate provides valuable insights. Additionally, the extreme ERS charging shares assume that drivers are fully aware of their driving and charging schedules in advance, which might not be the case. Probable ERS charging shares are expected to be in between these limits.

2) ERS placement

Among investigated scenarios, E&N25 costs about €2-€13 billion and yields net benefits from reduced battery sizes of €23-€34 billion, whereas E&N100 costs 4 times more (€8-€51 billion) and could yield negative net savings. The results show the importance of implementing ERS with low estimated costs to assure higher net savings on E&N100. On the other hand, the E&N25 placement scenario has greater flexibility with respect to ERS costs. Economically, it is reasonable to utilize shorter ERS distances with high traffic (e.g., E&N25) at early stages. This is consistent with [4], which find that utilization of E&N25 alone could result in the electrification of 70% of the traffic on E and N roads and 35% of the total traveled vehicle kilometers in Sweden. However, more ERS distances would increase the ERS utilization and probably encourage people to adapt the ERS option to charge their vehicles. For E&N25, eliminating stationary charging altogether (NoSC) is harder because it requires very large battery ranges compared to much smaller battery ranges for E&N100. However, proper placement of the same ERS lengths that provides reasonable equal opportunity for cars to use ERS is needed besides considering roads according to major long-haul truck flows.

3) Reduced battery ranges with stationary charging

The modeled required battery ranges for cars represent the optimal minimum ranges with ERS. Realistically, batteries are not manufactured specifically for each driver. However, the analysis shows that with ERS, the required battery range to complete all driving is small for most vehicles. Similarly, [12] show that 97.7% of the trips in the USA could be fulfilled with a 40 km BEV considering both stationary and ERS charging. BEVs with the option to reduce large battery ranges could be targeted in the early stages to maximize benefits. The results show that in most cases the economic benefits from the reduction in battery range and charging infrastructure are greater than the associated costs of installing ERS. This finding is consistent with [7] for Denmark and [12] for the US, which show that ERS is cheaper than the additional costs of larger battery ranges.

With ERS, public stationary chargers could be completely eliminated while maintaining most of the maximal savings from reduced battery sizes. Completely eliminating stationary charging (i.e., NoSC) will not work for all vehicles even with large batteries. However, a share of the vehicles, especially urban residents, could complete their driving with smaller battery ranges.

Operating an ERS does not guarantee users rely on ERS as expected to charge their vehicles nor choosing BEVs with the optimal battery ranges [12], thus influencing the expected savings. Many variables could influence the driver's charging preference, e.g. battery prices, annual driving, charging rate and electricity prices on ERS and stationary chargers [15], [21], [50]. Drivers could resort to increasing their BEV battery range over the minimum to have more charging options in their trips. Increasing the fleet's battery ranges (capacities) by 28 km (~5 kWh) means losing a maximum of €2.5 billion from savings. Implemented ERS technology should be appealing to users to ensure higher ERS utilization and more savings. But minimum ERS charging share analysis shows that even if car users increase their battery ranges, they need ERS charging to complete their trips. The analysis also shows that for BEVs to use small batteries both charging options are required, making each charging option complementary to the other.

4) Charging rate

How large ERS charging power could be achieved is still being investigated, and different companies are proposing different charging powers between 20 kW-200 kW for different vehicle types, i.e., under our charging rate assumptions $\approx 1.1e - 11.1e$ [12], [15], [21], [25], [26]. The study identifies the importance of developing ERS with high charging rate technologies for BEVs (e.g., 4e) if the objective is to eliminate stationary charging. The focus should then be on technologies that can be used by both private vehicles and heavy trucks, i.e., that provide sufficient charging power for heavy trucks while allowing for relatively high charging power for private BEVs. Utilizing ERS technology with a high charging rate for BEVs is still a technical challenge. For instance, with charging rates that serve trucks (i.e., charging power = 130 - 200 kW), current pickup systems for cars can transfer charging power of 50 kW [4], which is less than the investigated 4e (charging power = 72 kW under our charging rate assumptions).

For wear and longevity reasons, current BEV batteries are often limited in charging power to a C rate of around 1 to 2 kW/kWh, that is, a full charge will take at least between 30 and 60 minutes. This is an inconvenience for a BEV compared to an ICE, which is filled up in a few minutes. The saved battery costs in our estimate rely on sometimes very small batteries: for instance, for the E&N25(2e) around 20% of the cars require battery ranges less than 50 km (~ 10 kWh), as depicted in Fig. 4.A. For these batteries, the assumed 2*e* charging power will be around 2C or more. Thus, bigger batteries ranges could be utilized with such cars.

Utilizing the option to lower the ERS investment cost by covering only limited segments of the road will further increase the charging power on these segments if the average delivered power is to be kept constant. Such savings may thus rely on further development of car batteries to tackle higher C rates. Of course, restricting the minimization of the batteries will relieve any requirement but then also restrict battery potential savings. It may be noted, though, that development of batteries towards higher C rates will also help diminish the inconvenience of a competitive fast charging system.

B. Future work

This research does not consider the economic gains to busses and trucks, which can be significant and are the main motivation for installing ERS in the first place. In addition, other savings for private vehicles including the saved charging time and the saved costs from reduced CO2 emissions are not quantified. Future research can investigate these economic effects in greater detail.

Acknowledgment

The authors would like to thank Jakob Rogstadius for his comments and reviews that helped improve the quality of this manuscript.

REFERENCES

[1] P. Stelling, "Policy instruments for reducing CO2-emissions from the Swedish freight transport sector," *Res. Transp. Bus. Manag.*, vol. 12, pp. 47–54, 2014, doi:

10.1016/j.rtbm.2014.08.004.

[2] Swedish Environmental Protection Agency, “Fördjupad analys av den svenska klimatomställningen 2020 - Klimat och luft i fokus (In-depth analysis of the Swedish climate transition 2019 - Climate and air pollution in focus),” Swedish Environmental Protection Agency, Stockholm, Sweden, 2020. [Online]. Available: http://www.naturvardsverket.se/978-91-620-6945-2.

[3] F. Chen, N. Taylor, and N. Kringos, “Electrification of roads: Opportunities and challenges,” *Appl. Energy*, vol. 150, pp. 109–119, 2015, doi: 10.1016/j.apenergy.2015.03.067.

[4] M. Taljegard, L. Thorson, M. Odenberger, and F. Johnsson, “Large-scale implementation of electric road systems: Associated costs and the impact on CO 2 emissions,” *Int. J. Sustain. Transp.*, vol. 14, no. 8, pp. 606–619, 2019, doi: 10.1080/15568318.2019.1595227.

[5] J. Jöhrens, H. Helms, G. Nebauer, and D. Jelica, “Feasibility Study of Swedish-German Corridor with Electric Road System,” in *Annual Transport Conference at Aalborg University*, 2020, pp. 1–4.

[6] S. Kühnel, F. Hacker, and W. Görz, “Oberleitungs-Lkw im Kontext weiterer Antriebs- und Energieversorgungsoptionen für den Straßengüterfernverkehr,” 2018. [Online]. Available: https://www.oeko.de/fileadmin/oekodoc/StratON-O-Lkw-Technologievergleich-2018.pdf.

[7] D. Connolly, “A comparison between oil , battery electric costs,” pp. 1–43, 2016.

[8] M. Taljegard, L. Göransson, M. Odenberger, and F. Johnsson, “Spacial and dynamic

energy demand of the E39 highway – Implications on electrification options," *Appl. Energy*, vol. 195, pp. 681–692, 2017, doi: 10.1016/j.apenergy.2017.02.025.

[9] P. Fyhr, G. Domingues, M. Andersson, F. J. Márquez-Fernández, H. Bängtsson, and M. Alaküla, "Electric roads: Reducing the societal cost of automotive electrification," *2017 IEEE Transp. Electrif. Conf. Expo, ITEC 2017*, pp. 773–778, 2017, doi: 10.1109/ITEC.2017.7993367.

[10] J. Willerström, "Modelling CO2 emissions from passenger cars for Swedish municipalities Swedish municipalities," 2019.

[11] N. Lutsey and M. Nicholas, "Update on electric vehicle costs in the United States through 2030," *Int. Counc. Clean Transp.*, no. June, pp. 1–12, 2019, [Online]. Available: https://theicct.org/sites/default/files/publications/EV_cost_2020_2030_20190401.pdf.

[12] B. J. Limb *et al.*, "Economic Viability and Environmental Impact of In-Motion Wireless Power Transfer," *IEEE Trans. Transp. Electrif.*, vol. 5, no. 1, pp. 135–146, Mar. 2019, doi: 10.1109/TTE.2018.2876067.

[13] G. Berckmans, M. Messagie, J. Smekens, N. Omar, L. Vanhaverbeke, and J. Van Mierlo, "Cost projection of state of the art lithium-ion batteries for electric vehicles up to 2030," *Energies*, vol. 10, no. 9, 2017, doi: 10.3390/en10091314.

[14] M. Taiebat and M. Xu, "Synergies of four emerging technologies for accelerated adoption of electric vehicles: Shared mobility, wireless charging, vehicle-to-grid, and vehicle automation," *J. Clean. Prod.*, vol. 230, pp. 794–797, 2019, doi:

10.1016/j.jclepro.2019.05.142.

[15] C. A. García-Vázquez, F. Llorens-Iborra, L. M. Fernández-Ramírez, H. Sánchez-Sainz, and F. Jurado, “Comparative study of dynamic wireless charging of electric vehicles in motorway, highway and urban stretches,” *Energy*, vol. 137, no. 2017, pp. 42–57, 2017, doi: 10.1016/j.energy.2017.07.016.

[16] Viktoria Swedish ICT, “Slide-in Electric Road System,” Gothenburg, Sweden, 2013. [Online]. Available: https://www.viktoria.se/sites/default/files/pub/www.viktoria.se/upload/publications/slide-in_inductive_project_report_draft_phase_1_2013-10-18.pdf.

[17] G. Domingues-Olavarría, F. J. Márquez-Fernández, P. Fyhr, A. Reinap, and M. Alaküla, “Electric roads: Analyzing the societal cost of electrifying all Danish road transport,” *World Electr. Veh. J.*, vol. 9, no. 1, pp. 1–11, 2018, doi: 10.3390/wevj9010009.

[18] E. den Boer, S. Aarnink, F. Kleiner, and J. Pagenkopf, “Zero emissions trucks: An overview of state-of-the-art technologies and their potential,” 2013. [Online]. Available: https://www.cedelft.eu/publicatie/zero_emission_trucks/1399.

[19] Highways England, “Feasibility study: Powering electric vehicles on England’s major roads,” Transport Research Laboratory, Guildford, UK, 2015.

[20] M. Fuller, “Wireless charging in California: Range, recharge, and vehicle electrification,” *Transp. Res. Part C Emerg. Technol.*, vol. 67, pp. 343–356, 2016, doi: 10.1016/j.trc.2016.02.013.

[21] S. Li and C. C. Mi, “Wireless Power Transfer for Electric Vehicle Applications,” *IEEE J. Emerg. Sel. Top. POWER Electron.*, vol. 3, no. 1, pp. 4–17, 2015, doi:

10.1063/5.0032383.

[22] F. J. Marquez-Fernandez, G. Domingues-Olavarria, L. Lindgren, and M. Alakula, "Electric roads: The importance of sharing the infrastructure among different vehicle types," *2017 IEEE Transp. Electrif. Conf. Expo, Asia-Pacific, ITEC Asia-Pacific 2017*, 2017, doi: 10.1109/ITEC-AP.2017.8080780.

[23] Z. Chen, W. Liu, and Y. Yin, "Deployment of stationary and dynamic charging infrastructure for electric vehicles along traffic corridors," *Transp. Res. Part C Emerg. Technol.*, vol. 77, pp. 185–206, 2017, doi: 10.1016/j.trc.2017.01.021.

[24] Swedish Transport Administration, "Trafikverket," *Trafikverket*, 2019. https://www.trafikverket.se/en.

[25] Y. J. Jang, "Survey of the operation and system study on wireless charging electric vehicle systems," *Transp. Res. Part C Emerg. Technol.*, vol. 95, no. March, pp. 844–866, 2018, doi: 10.1016/j.trc.2018.04.006.

[26] T. E. Stamati and P. Bauer, "On-road charging of electric vehicles," *2013 IEEE Transp. Electrif. Conf. Expo Components, Syst. Power Electron. - From Technol. to Bus. Public Policy, ITEC 2013*, 2013, doi: 10.1109/ITEC.2013.6573511.

[27] S. Karlsson, "The Swedish car movement data project Final report," pp. 1–12, 2013.

[28] N. Jakobsson, T. Gnann, P. Plötz, F. Sprei, and S. Karlsson, "Are multi-car households better suited for battery electric vehicles? - Driving patterns and economics in Sweden and Germany," *Transp. Res. Part C Emerg. Technol.*, vol. 65, pp. 1–15, 2016, doi: 10.1016/j.trc.2016.01.018.

[29] "Copernicus," 2018. https://www.copernicus.eu/en.

[30] W. Shoman and H. Demirel, “Impedance measures in evaluating accessibility change,” *Geocarto Int.*, pp. 1–16, 2020, doi: 10.1080/10106049.2020.1869327.

[31] W. Shoman, U. Alganci, and H. Demirel, “A comparative analysis of gridding systems for point-based land cover/use analysis,” *Geocarto Int.*, vol. 34, no. 8, pp. 867–886, 2019, doi: 10.1080/10106049.2018.1450449.

[32] L. H. Björnsson and S. Karlsson, “Plug-in hybrid electric vehicles: How individual movement patterns affect battery requirements, the potential to replace conventional fuels, and economic viability,” *Appl. Energy*, vol. 143, pp. 336–347, 2015, doi: 10.1016/j.apenergy.2015.01.041.

[33] B. Nykvist and M. Nilsson, “Rapidly falling costs of battery packs for electric vehicles,” *Nat. Clim. Chang.*, vol. 5, no. 4, pp. 329–332, 2015, doi: 10.1038/nclimate2564.

[34] E. A. Olivetti *et al.*, “Automotive Lithium-ion Cell Manufacturing: Regional Cost Structures and Supply Chain Considerations,” *Joule*, vol. 1, no. 2, pp. 229–243, 2016, [Online]. Available: www.nrel.gov/publications.%0Ahttp://www.osti.gov/servlets/purl/1333041/%0Ahttps://doi.org/10.1016/j.joule.2017.08.019.

[35] O. Schmidt, A. Hawkes, A. Gambhir, and I. Staffell, “The future cost of electrical energy storage based on experience rates,” *Nat. Energy*, vol. 2, no. 8, pp. 1–8, 2017, doi: 10.1038/nenergy.2017.110.

[36] R. Schmuch, R. Wagner, G. Hörpel, T. Placke, and M. Winter, “Performance and cost of materials for lithium-based rechargeable automotive batteries,” *Nat. Energy*, vol. 3, no. 4, pp. 267–278, 2018, doi: 10.1038/s41560-018-0107-2.

[37] K. Mongird *et al.*, “Energy storage technology and cost characterization report,” *Pacific Northwest Natl. Lab.*, no. July, pp. 1–120, 2019, [Online]. Available: https://www.energy.gov/sites/prod/files/2019/07/f65/Storage Cost and Performance Characterization Report_Final.pdf.

[38] S. Karlsson, “Utilization of battery-electric vehicles in two-car households: Empirical insights from Gothenburg Sweden,” *Transp. Res. Part C Emerg. Technol.*, vol. 120, no. September, p. 102818, 2020, doi: 10.1016/j.trc.2020.102818.

[39] O. Hjortsberg, “Slide In-teknik för kontinuerlig överföring av energi till elektriska fordon, Fas2,” Stockholm, 2018.

[40] J. Kristensson, “Är elvägar lösningen på en ”monumental utmaning”?,” *NyTeknik*, Mar. 2020.

[41] World Road Association (PIARC), *Electric Road Systems: a solution for the future?* 2018.

[42] Iea *et al.*, “Electric vehicles in Europe :,” *Energy*, vol. 3, no. June, p. 33, 2014, [Online]. Available: https://www.toi.no/getfile.php/Publikasjoner/T�I rapporter/2013/1281-2013/1281-2013-elektronisk.pdf%5Cnhttp://wrs.region-stuttgart.de/sixcms/media.php/923/Electric Mobility Pilot Region_english.pdf%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=.

[43] T. Chen *et al.*, “A Review on Electric Vehicle Charging Infrastructure Development in the UK,” *J. Mod. Power Syst. Clean Energy*, vol. 8, no. 2, pp. 193–205, 2020, doi: 10.35833/MPCE.2018.000374.

[44] R. Brazil, “Recharging the future,” *Educ. Chem.*, vol. 54, no. 2, pp. 24–27, 2017.

[45] European Parliament and Council, *Directive 2014/94/EU of the European Parliament and the Council of 22 October 2014 on the deployment of alternative fuels infrastructure, 10 2014*. THE EUROPEAN PARLIAMENT AND OF THE COUNCIL, 2014.

[46] T. Gnann, S. Funke, N. Jakobsson, P. Plötz, F. Sprei, and A. Bennehag, "Fast charging infrastructure for electric vehicles: Today's situation and future needs," *Transp. Res. Part D Transp. Environ.*, vol. 62, no. March, pp. 314–329, 2018, doi: 10.1016/j.trd.2018.03.004.

[47] Statistics Sweden, "Passenger cars in use by region and type of ownership. Year 2002 - 2019," 2019. http://www.statistikdatabasen.scb.se/pxweb/en/ssd/START__TK__TK1001__TK1001A/PersBilarA/.

[48] S. Karlsson, "What are the value and implications of two-car households for the electric car?," *Transp. Res. Part C Emerg. Technol.*, vol. 81, pp. 1–17, 2017, doi: 10.1016/j.trc.2017.05.001.

[49] S. Kagawa *et al.*, "Better cars or older cars?: Assessing CO2 emission reduction potential of passenger vehicle replacement programs," *Glob. Environ. Chang.*, vol. 23, no. 6, pp. 1807–1818, 2013, doi: 10.1016/j.gloenvcha.2013.07.023.

[50] Z. Bi, T. Kan, C. C. Mi, Y. Zhang, Z. Zhao, and G. A. Keoleian, "A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility," *Appl. Energy*, vol. 179, pp. 413–425, 2016, doi: 10.1016/j.apenergy.2016.07.003.